Estimating the Universal Positions of Wireless Body Electrodes for Measuring Cardiac Electrical Activity

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***Abstract*—A methodology is presented for estimating the wireless body electrode (WE) positions and for calculating the linear transformations that enable the synthesis of a 12-lead ECG or a multichannel ECG from three WEs, which in turn simplifies and improves the acquisition of ECGs. We present, compare and evaluate three approaches to the synthesis: fully personalized, fully universal, and combined with universal leads and personalized transformations. The evaluation results show that WEs are an acceptable alternative to the standard 12-lead ECG device for patients with chronic myocardial ischemia, if either the fully personalized or combined approach is used. The median correlation coefficients are all higher than 0.94 and 0.92 for the fully personalized and combined approaches, respectively. The corresponding kappa and percentual diagnostic agreements between the synthesized and target 12-lead ECGs are 0.88 (95%) and 0.83 (92%), respectively. The evaluation additionally shows that the personalization of the transformations has more impact on the quality of the synthesized ECGs than the personalization of the WEs' positions.**

***Index Terms*—Derived electrocardiograms, Differential leads, ECG synthesis, Electrocardiography, Wireless electrodes.**

I. Introduction

The application of a conventional 12-lead ECG device can be impractical, particularly in emergency situations, since the accurate standard positions of the precordial electrodes are difficult to locate quickly, particularly in women and children. Furthermore, the recording of a 12-lead ECG can be inconvenient for long-term and mobile applications. Systems with reduced numbers of leads that can synthesize a 12-lead ECG with an insignificant or a small loss of diagnostic information have been proposed [1]. The advantage over standard 12-lead ECG systems is the smaller number of measurement sites (i.e., electrodes) and, consequently, fewer wires. Lead systems with reduced numbers of leads that synthesize 12-lead ECGs are commonly referred to as derived 12-lead ECG systems.

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One of the most promising derived 12-lead ECG systems uses leads measured with a wearable ECG device called a wireless body electrode (WE) [2], [3], [4], [5]. These WEs enable the use of a minimal number of wires on the body and so increase the wearable comfort. The WEs measure and wirelessly transmit only the local potential differences, i.e., the bipolar measurements from two closely placed skin electrodes.

In our previous study [6] we investigated a personalized approach to the synthesis of a 12-lead ECG from three leads that can be measured with WEs, which we called differential leads (DLs). An algorithm was presented that determines the personalized measurement points (i.e., the electrodes' positions) for three DLs, and a personalized transformation matrix used for the synthesis of the 12-lead ECG. The optimum number of DLs is three, which was determined experimentally, but can also be rationalized theoretically [7], [8], [9]. The ECGs synthesized in this way were compared to the EASI [10] synthesis and showed higher quality in terms of the correlation coefficient (CC) and the root-mean-square distance (RMSD). Even though the presented, fully personalized approach is expected to yield the synthesis of the highest quality it has a practical drawback in that it requires a multichannel ECG (MECG) to be pre-recorded for any person planning to use the WEs.

In the present study we investigate the other two synthesis possibilities: one is to determine the universal measuring positions and the universal transformation, whereas the other is to keep the universal positions but employ a personalized transformation matrix. The latter method is expected to yield ECGs of better quality than the former, but it requires a 12-lead ECG and the leads from WEs' universal positions to be recorded simultaneously in order to calculate the personalized transformation matrix in a process sometimes referred to as calibration [11]. All three approaches are evaluated by standard evaluation measures, but we also used evaluation approaches that are particularly applicable for our patient population.

II. Methods

The DLs measurements used in the following methods were emulated by the differences between the unipolar leads of a MECG (see [6] for details).

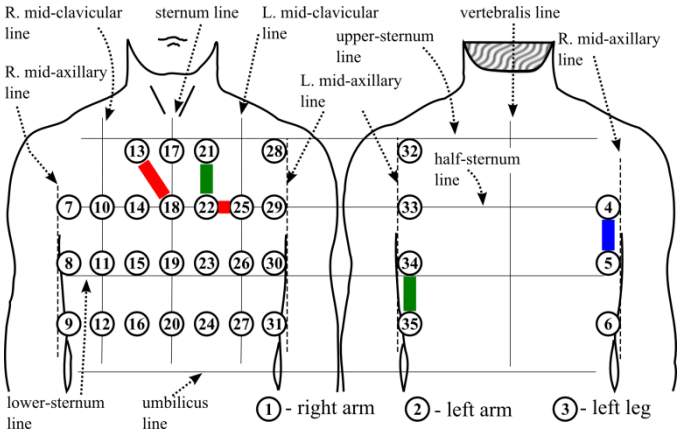

Fig. 1. Schematic locations of MECG electrodes on the chest (left) and the back (right). The leads indicated by red lines are the calculated best leads for the 12-lead ECG synthesis, whereas the ones indicated by green lines are the calculated best leads for the MECG synthesis. The lead indicated in blue is in both sets of best leads.

A. *Studied Data*

Twenty healthy volunteers (13 male, 7 female, mean age ± SD = 50.6±9) with no previous medical record related to heart disease and with a normal 12-lead ECG, and twenty-seven patients (22 male, 5 female, mean age ± SD = 58±10), scheduled for a bypass or grafting surgery, were included in our study. The patients had one or multiple significant coronary artery stenoses, whereas eight of them had an old myocardial infarction. Informed consent was obtained from all the subjects before the study. A single MECG measurement was obtained from each volunteer and two MECG measurements from each patient who underwent surgery: the first, one day before the surgery, and the second, in the period from the fifth to the seventh day after the surgery. No attempt was made to exclude any measurement; therefore, a few measurements have arrhythmic events. The measurements were obtained during our previous studies [12].

The procedure for recording the data is summarized as follows. We have developed a custom MECG device with 35 electrodes, all referenced to the Wilson central terminal potential (see [13] for details). The locations of the electrodes are shown schematically in Fig. 1. All the MECG measurements also incorporate all the electrodes for the simultaneous measurement of a standard 12-lead ECG.

All the data were immediately examined for the quality of the signals from each individual electrode. In the case of a defective measurement, the cause of the disturbance was identified and the problem was immediately solved. Data acquisition was then restarted, following the same protocol. The measured MECG analog signals were sampled at 1000 Hz and digitized with a 0.73 μV resolution (14-bit analog-digital converter). The bandwidth of the recording system was 0.05 to 250 Hz. The length of each measurement was 360 seconds.

B. *Data Preprocessing*

The recorded signals were imported and further processed using MatLab (MathWorks, Inc.). First, a series of R-peak times - fiducial points, were detected for each MECG using a dedicated software function, which is based on the Pan & Tompkins algorithm [14]. The function first applies a differentiator filter that calculates the differences between neighboring samples [15]. Then, a fixed threshold is applied to the differentiator's output. The R-peaks are determined by finding the maximum signal amplitude for samples that lie above the threshold. The threshold values were calculated separately for each MECG as

$$0.3 \cdot mean(derivatives\ above\ 99th\ percentile).$$

Next, an isoelectric point in the middle of the PQ segment was detected for a single beat of each MECG by the procedure described in [16], and confirmed by visual inspection. The distance between the isoelectric point and its corresponding (nearest right) fiducial point was used to determine all the other isoelectric points (the distance is subtracted from the fiducial points) as it was assumed that the distances between the isoelectric points and the fiducial points are nearly constant for all the beats in a single MECG. The determined isoelectric points were visually inspected in the figures, each with all the beats in a single MECG aligned by their fiducial points, and overlaid. The visual inspections indicated undistinguishable variations in the distances between the fiducial points and the isoelectric points in each MECG, which in turn confirmed the initial assumption of the distance constancy between the fiducial and isoelectric points. The baseline wandering was removed from all the measurements by interpolating a cubic spline through the isoelectric points of each MECG lead and subtracting it from the source lead. This technique does not significantly distort the ECG morphology [16].

Subsequently, 10-second intervals were randomly extracted from each measurement, visually examined for the signal quality and filtered by a low-pass filter with a cutoff frequency of 40 Hz, an attenuation of 60 dB, and a stop frequency of 100 Hz. These extracted measurements represent realistic signals that can be measured using WEs and have therefore been used for the evaluation of the synthesis algorithms (evaluation intervals).

From the remaining parts of the measurements, the average beats were obtained by time-aligning beats in each lead with their fiducial points, adding the beats together, and dividing by the number of beats. The average beats were calculated from the non-filtered signals, since the high-frequency noise is satisfactorily damped by the averaging [16]. The average beats were then compared, visually and by CC and RMSD [17], with all the beats in the corresponding leads, for the purpose of identifying and eliminating the eventual ectopic beats and the beats with the eventual remaining measurement errors. The remaining beats were used to calculate the final average beats, which were used in all the subsequent processing, except in the evaluation of the synthesized ECGs.

For evaluation purposes, the average beats were calculated for each lead of both the target and the synthesized evaluation intervals, by using the same procedure described for complete MECGs. The J-points were determined using the same assumption as for the isoelectric points - the distances between the corresponding fiducial point and the J-points are nearly constant for all the beats in a single MECG. Hence, a J-point

was detected on one evaluation interval's average beat for each MECG, using the procedure described in [16], and verified by visual inspection. The J-points for the remaining average beats were calculated by adding the distance to their fiducial points.

C. Calculation of Universal DL Positions and Universal Transformation

For the universal synthesis we employed a method of juxtaposing measurements that was previously used in other studies (e.g., [18]): the average beats from each MECG were concatenated for each lead. The obtained all-embracing measurement was used as the input for our "Best DLs selection algorithm", described in [6]. The algorithm basically performs a full search over all the possible combinations of DL, formed by the differences of the neighboring unipolar MECG leads, for the purpose of synthesizing the 12-lead ECG. The declared best DLs combination is the one that produces the synthesized 12-lead ECG with the highest correlation to the target measured 12-lead ECG. For the juxtaposed average beats, the algorithm yields the best universal combination of three DLs, and an universal transformation matrix $\boldsymbol{b} = [3 \times 12]$, which is the best universal transformation in the least-squares sense. Matrix $\boldsymbol{b}$ can be used to transform the three universal DLs, measured on any person, to a synthesized 12-lead ECG

$$\widehat{\boldsymbol{E}} = \boldsymbol{M} \cdot \boldsymbol{b}, \tag{1}$$

where $\widehat{\boldsymbol{E}}$ is a synthesized 12-lead ECG, and $\boldsymbol{M}$ is a matrix

$$\boldsymbol{M} = \begin{bmatrix} DL(1)_1 & DL(2)_1 & DL(3)_1 \\ \vdots & \vdots & \vdots \\ DL(1)_n & DL(2)_n & DL(3)_n \end{bmatrix}, \tag{2}$$

with universal DL samples in its columns (n is the total number of samples).

D. Calculation of Personalized Transformations for Universal DL Positions

We calculated the personalized transformations for the universal DL positions by fitting a linear model between the average beats of the target 12-lead ECG and the average beats of the measured universal DLs for each person. The models' transformation matrices were again estimated using the least-squares method. It is clear that the simultaneous measurements from the universal DLs and from the target 12-lead ECG are needed. We will refer to this synthesis approach as the combined approach.

E. Calculation of Personalized Transformations for Personalized DLs

This fully personalized approach was explored in our pervious study [6], where the personalized DLs and transformations were calculated by using measurement intervals, not the average beats. Nevertheless, to enable a direct comparison between all three approaches, we recalculated the personalized DLs and transformations by using the same algorithm as in [6], but utilizing the average beats instead of the measurement intervals. The synthesis was evaluated on the same evaluation intervals and using the same evaluation measures as the other two approaches.

F. MECG Synthesis

In addition to the 12-lead ECG synthesis, the MECG leads were also synthesized using the same methods as described in Sections II.C, II.D, II.E, with the only difference being that the target ECG used in the calculation of the best DLs and transformations is the MECG, i.e., its average beats. Equations (1) and (2) are still valid for the MECG synthesis but $\widehat{\boldsymbol{E}}$ now has the meaning of a synthesized MECG, and $\boldsymbol{b}$ is a $[3 \times 35]$ matrix. The MECG leads are not diagnostically as significant as the 12-lead ECG [19], but the synthesis of MECG leads has an additional purpose because it reveals, together with the synthesized 12-lead ECG, how well the total body-surface potential map can be restored from the DLs.

G. Evaluation Methods

The accuracy of the 12-lead ECG synthesis was evaluated by comparing it to the target ECG, on the evaluation segments, with the following means: a visual comparison, CC, the ST segment level at 60 ms after the J-point (ST60), and the ST segment's slope. The visual comparison with the target 12-lead ECG classified the synthesized leads as identical or clearly different. An expert cardiologist was engaged to visually examine the target and the synthesized 12-lead ECGs. The ST60 and ST-slopes were taken from the average beats calculated from the ten-second evaluation intervals (target and synthesized). The ST-slopes were calculated as the mean ST-segment gradients from the J-point to the point 60ms after the J-point.

Since the exploited ECG measurements come from patients with diagnosed myocardial ischemia, the ECGs were also evaluated by employing a well-known diagnostic rule for detecting myocardial ischemia that is based on the ST segment elevation (or depression) and the T wave abnormalities. The rule is described in [20] and was also used in previous studies (e.g., [21], [22]).

The diagnostic rules for ischemia are not well established for leads outside the 12-lead ECG set [19]; therefore, the MECG synthesis was only evaluated using the CC and ST-segment features.

III. Results

The best DLs selection algorithm gave the following set of DLs for the universal 12-lead ECG synthesis: $\{(13,18),(4,5),(22,25)\}$, whereas for the MECG synthesis the best DLs are: $\{(21,22),(4,5),(34,35)\}$. The best DL sets are marked in Fig. 1.

The best DL selection algorithm is based on maximizing the minimum CC among the synthesized leads (CC_{min}) as it represents the worst synthesized lead [6]. Fig. 2 shows histograms of DL combinations for the CC_{min} intervals. This illustrates the importance of finding the best DLs, because the number of combinations with high CC_{min} is very small, relative to the total number of combinations. Interestingly, the

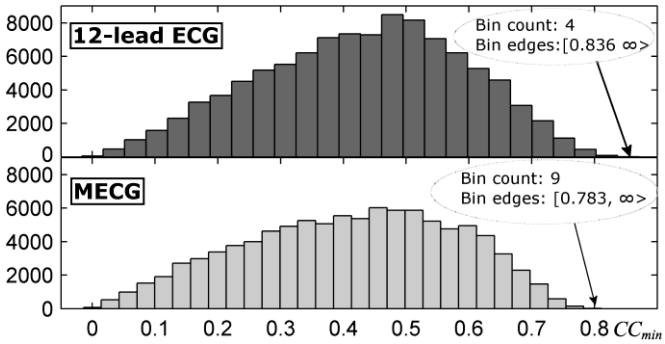

Fig. 2. The number of DL combinations for the CC_{min} intervals, for the universal 12-lead ECG synthesis (upper histogram) and the universal MECG synthesis (lower histogram). The data for the rightmost bins are shown in the balloons.

algorithm gave different best DL combinations for the 12-lead ECG and for the MECG synthesis; however, the best DLs for the MECG are the fourth best in the sorted list of best DL combinations for the 12-lead ECG, with the CC_{min} being only 0.024 smaller than the CC_{min} for the best 12-lead ECG's DL combination. Therefore, for practical reasons the best combination of DLs for the MECG synthesis could also be used for the 12-lead ECG syntheses without any significant loss in the synthesis quality. However, in the present study we have evaluated the MECG and the 12-lead ECGs obtained from their associated best combinations of DLs.

Fig. 3 shows an example of the target and synthesized 12-lead ECGs for a patient before a surgery. We selected an ECG interval that contains an extrasystole, which represents an additional difficulty for the ECG synthesis, because the origin of extrasystolic cardiac activity is located on different position compared to normal beats [23], so a different transformation would be required [24]. This is indicated by smaller CCs.

To estimate the significance of the regressions for the 12-lead ECG and the MECG, employed for calculating the universal DL positions (Section II.C), we calculated the p-values for the F-statistics. The p-values were all insignificantly different than 0, which indicates a very high regression significance [25]. Furthermore, we calculated the normalized 95% confidence interval lengths for the coefficient estimates $\boldsymbol{b}$, by dividing the lengths by the corresponding coefficient estimates. The median values and interquartile ranges for the normalized confidence intervals are $0.019\,[0.012, 0.04]$ for the MECG synthesis and $0.015\,[0.01, 0.026]$ for the 12-lead ECG synthesis, which shows that the studied data were of a satisfactory size for the universal synthesis, i.e., that a satisfactory number of measurements was used.

A. Evaluation by Visual Comparison

Table I shows the evaluation results obtained by visual comparison of the target and synthesized leads. Two independent observers, first is a medical doctor, cardiologist, and second with an extensive technical knowledge of ECG devices and cardiac electrophysiology, have visually inspected all 12-lead ECGs, target and synthesized. The ECG leads were presented in the same way as in Fig. 3, but in a higher

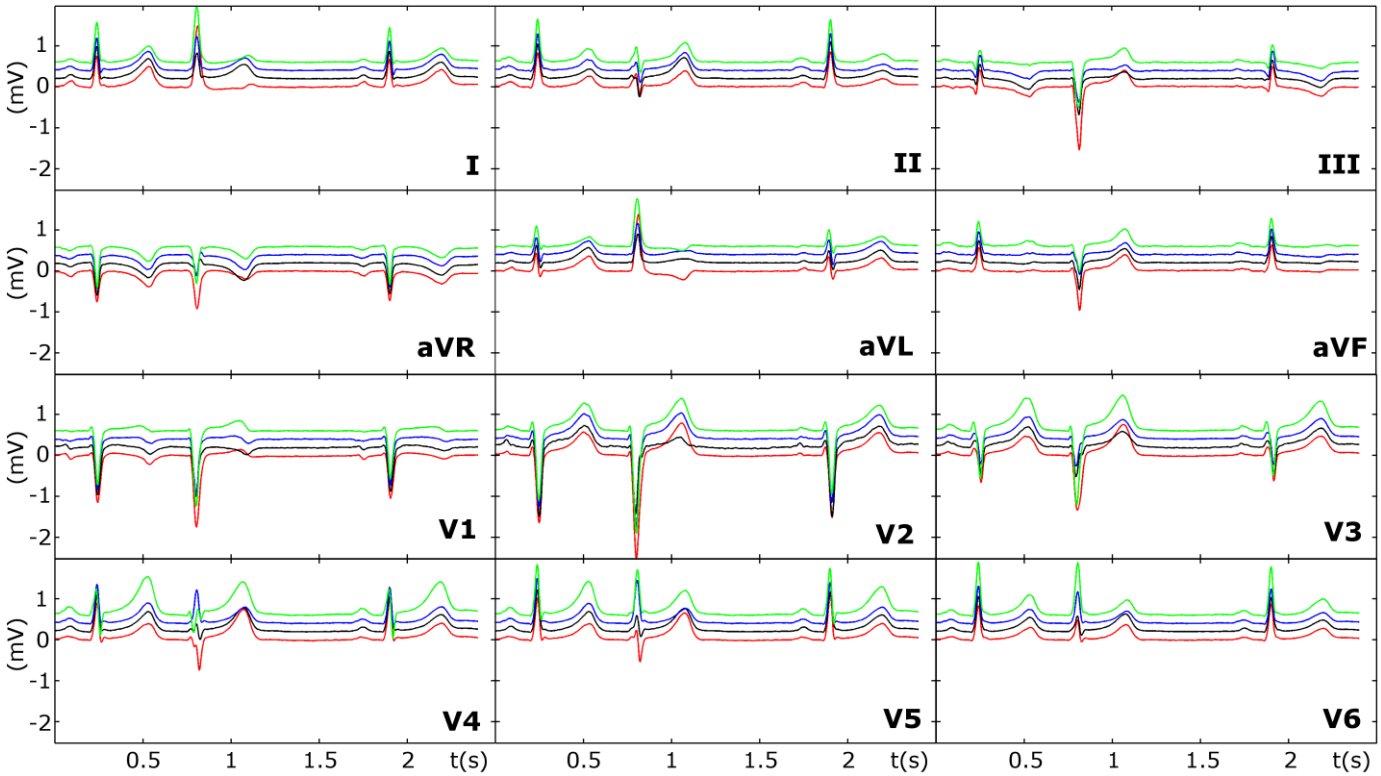

Fig. 3. 12-lead ECGs for a patient before surgery. The figure shows the target 12-lead ECG (bottom curve) and the synthesized 12-lead ECGs, moved relative to each other by 0.2 mV, in this order: fully personalized synthesis (black), combined synthesis (blue), fully universal synthesis (green). The presented part of the evaluation interval contains an extrasystole (second beat). On the whole presented interval, the minimum CCs between the three synthesized ECGs, and the target ECG are 0.77, 0.69, 0.77 in the order as the synthesized ECGs are plotted. The minimum CCs are found in leads I, V4, V4, respectively. The minimal CCs calculated just for the third (normal) beat are 0.99, 0.98, 0.8, in leads aVL, V1, V4. The obtained personalized DLs were {(10,14), (14,19), (29,30)}.

TABLE I
PERCENTAGE OF THE SYNTHESIZED LEADS VISUALLY DIFFERENT FROM THE TARGET LEADS

Synth. type	I	II	III	aVR	aVL	aVF	V1	V2	V3	V4	V5	V6
Full Univ.	21.6	10.8	44.6	14.9	17.6	21.6	25.7	6.8	25.7	41.9	37.8	20.3
Combined	2.7	4.1	6.8	2.7	2.7	2.7	8.1	2.7	18.9	23.0	21.6	0

Note that for the fully personalized synthesis there was no lead tagged as clearly different.

resolution and on the paper with 1mm squares. A few extrasystoles, present in evaluation intervals, were not analyzed. A lead was tagged by "clearly different" if the ECG waves or levels differ in morphology (shape, orientation), in duration (for more than 40 ms), or in amplitude (for more than 0.2 mV in QRS or T, and 0.1 mV in P or ST-level). The percentage of visually different synthesized leads for fully universal and combined synthesis is given in Table I. The fully personalized synthesis did not produce any lead that was visually clearly different from the target lead.

B. Evaluation by Correlation Coefficient

Fig. 4 shows the CCs between the target and the synthesized leads for the three syntheses possibilities. Surprisingly, there are a few leads, indicated with arrows, for which the median CC is significantly smaller in the fully personalized approach than in the combined or universal approach, or even in both for V2. Nevertheless, the median CCs for those seven cases are all higher than 0.945.

The minimum median CC for the fully personalized approach is 0.94 for lead 9, for the combined approach it is 0.92, again for lead 9, whereas for the fully universal approach it is 0.84 for lead 12. Considering only the 12-lead ECG the minimum medians are, respectively, 0.96, 0.95 and 0.84, all for lead III.

C. Comparison of ST60 and ST-slope Features

D. Table II shows the medians and interquartile ranges for the absolute differences between the ST60 and ST-slope features of the target and synthesized leads. The maxima and means are calculated between the leads of each measurement, whereas the medians and interquartile ranges (in parentheses) are calculated between the measurements. The data presented are for all the leads of the 12-lead ECG and MECG.Comparison of Diagnostic Rule Outcomes

Table III shows the comparison of the diagnostic rule outcomes between the target 12-lead ECGs and the

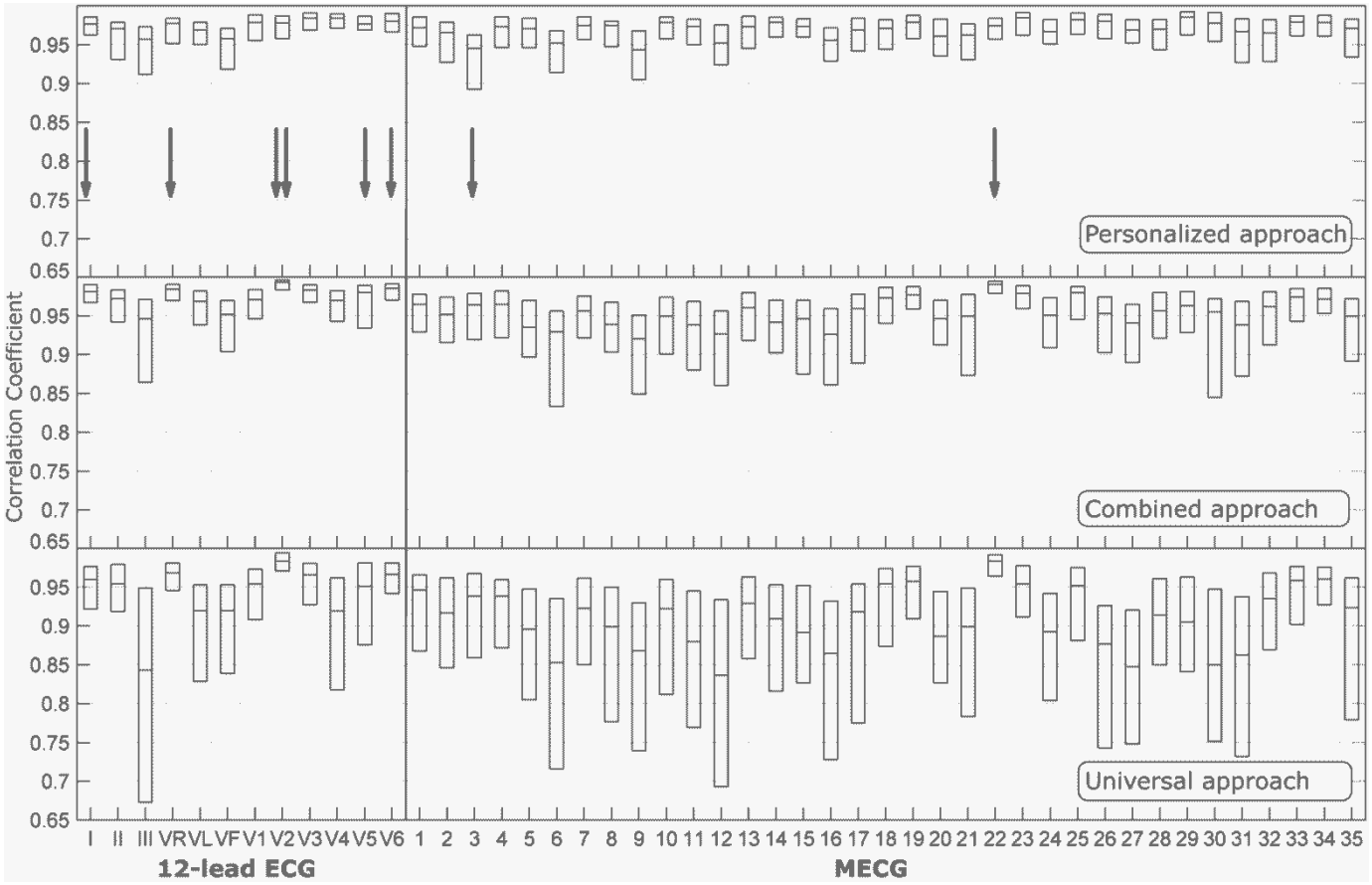

Fig. 4. CCs between the target and synthesized leads of the 12-lead ECG (I, II, … , V6) and the MECG leads (1, 2, … , 35). On each box the central mark is the median; the edges of the box are the 25th and 75th percentiles. The arrows indicate that a particular lead has a median CC for the personalized approach significantly smaller than in the combined approach. The double arrow for the lead V2 indicates that its median is also significantly smaller than in the universal approach. For all the other leads the medians are higher in the above graph, or the difference is not significant. The Wilcoxon signed rank test was used with a 5% significance level.

TABLE II
ST-SEGMENT FEATURES' DIFFERENCES BETWEEN TARGET AND SYNTHESIZED LEADS

Synthesis type	ST60 max. abs. diff. (μV)	ST60 mean abs. diff. (μV)	ST-slope max abs diff.(º)	ST-slope mean abs. diff. (º)
Full Univ.	87(68-118)	18(15-27)	13(10-19)	4(3-5)
Combined	50(36-65)	11(8-16)	13(9-21)	3(2-4)
Full Pers.	38(29-60)	10(7-12)	13(9-15)	2(2-3)

The results are given in median (range) format.

TABLE III
THE DIAGNOSTIC RULE OUTCOMES' AGREEMENTS BETWEEN TARGET AND SYNTHESIZED ECGS

Synthesis type	Kappa	Kappa conf. interval*	Percentage Agreement
Full Univ.	0.54	[0.34,0.75]	79.73
Combined	0.83	[0.71,0.96]	91.89
Full Pers.	0.88	[0.77,0.99]	94.59

* The kappa confidence interval is calculated for the 5% significance level.

synthesized ECGs. A considerable difference between the performance of the universal synthesis and the combined synthesis can be observed, especially in terms of the kappa statistic. Despite this, the percentage agreement for the fully universal synthesis is almost 80%. The difference between the combined and fully personalized synthesis is not so pronounced. The kappa confidence intervals are quite wide, which shows that the diagnostic rule application could benefit from additional measurements in this case.

IV. DISCUSSION

The visual comparison (Table I) shows a high percentage of visually different synthesized leads for the universal approach. Furthermore, there is an obvious difference in leads' visual quality between the three approaches. This is in accordance with the evaluation by CC, which indicates the superiority of the fully personalized approach, but also reveals that the combined approach provides a better synthesis than the universal approach.

The CC medians (Fig. 4), ST-segment features (Table II), and the diagnostic rule outcomes (Table III), all confirm the superiority of the personalized approach, but additionally reveal that there are much larger differences in the synthesis quality between the combined and universal approaches, than between the personalized and combined approach. This indicates that for the quality of the synthesized ECG, the personalization of the transformations is more important than the personalization of the DLs.

Table II shows that the ST60 differences might be high enough to potentially cause an error in ECG interpretation, for all three synthesis types, but the interpretation depends on the lead in which the ST60 difference has occurred, the lead's neighboring leads, and generally on the applied diagnostic rule, whose outcomes may be calculated automatically, or imposed by an expert.

We have therefore applied a well-known diagnostic rule for detecting myocardial ischemia. The results presented in Table III show high diagnostic concordances for the combined and personalized approaches. For the personalized approach in fact there are only four (of a total of 74) measurements for which the diagnostic rule outcomes were different for the target and synthesized 12-lead ECG: one false-negative and three false-positive cases. Our detailed investigation of the faulty synthesized ECGs revealed that the errors occurred because the residual noise in the evaluation intervals was over amplified during the synthesis. This problem may be resolved in the future by restricting the magnitude of the linear transformation coefficients, or by applying a more efficient low-pass filter to the measured ECG.

As expected, the universal approach provides the weakest performance as it does not take into account the individual electrical characteristics and the shape of the volume conductor, and the individual locations of the heart dipole [24], but it has the advantage that for its application there is no need for additional measurements or calculations, since the universal DLs and transformation are calculated only once. The combined and the fully personalized syntheses, on the other hand, provide considerably higher performance, but both have the practical drawback that a new measurement and calculation are needed for each person that will use the WEs. The combined approach requires the simultaneous measurement of the universal DLs and the 12-lead ECG, whereas the fully personalized approach requires a MECG measurement. Both cases generally require specialized equipment, but if it is not available, it is possible to obtain pseudo-simultaneous measurements, or MECGs, by using only a common 12-lead ECG device [26].

The universal approach is applicable in emergency situations, whereas for patients with ECG changes indicative of chronic myocardial ischemia, one of the main cardiovascular diseases, it is justifiable to perform the necessary measurements that enable personalized or combined approaches. As those patients should be monitored continuously, the application of WEs could be beneficial because it reduces the number of wires, and improves the comfort and applicability of a wearable ECG device.

V. CONCLUSION

The evaluations presented in this study show that the WEs are an acceptable alternative to the standard 12-lead ECG device for patients with chronic myocardial ischemia, especially if the presented combined or the fully personalized approach is applied. The universal synthesis approach may possibly be improved in the future with a segment-specific synthesis (different transformations for each ECG segment) but such an approach would also require automatic and reliable real-time segments extraction from the WE measurements. Future investigations, with the methodology presented here, and applied to patients with other diseases, could provide definitive justifications for the WEs-derived 12-lead ECG system.

The sensitivity of the 12-lead ECG to the detection of myocardial ischemia is not very high [20]. Therefore, a number of researchers have investigated the applicability of additional leads for this purpose [19]. Our investigation of the MECG leads' synthesis shows that the CCs for the MECG are

comparable to the CCs obtained for the 12-lead ECG syntheses, which indicates that a high-quality MECG synthesis is possible just from three DLs. The synthesized MECG leads may be used in future for detailed ischemia detection, by applying a reliable diagnostic rule when it becomes available.

We have shown that the number of DLs combinations that produce high-quality synthesized ECGs (Fig. 2) is relatively small for both MECG and 12-lead ECG universal syntheses, but still large enough that another combination of DLs could be applied, without a significant loss in synthesis quality, if for some anatomic or ergonomic reasons the best DLs combination is inconvenient for WE placement. This is an additional advantage of WEs over a standard 12-lead ECG device, and derived ECG systems that employ fixed measurement points. Furthermore, the freedom to choose between several combinations of WEs positions also makes it possible to monitor cardiac electrical activity during therapeutic procedures that could disturb or disable the application of a standard 12-lead ECG device.

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